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Description Exact automatic differentiation for R functions. Provides a composable derivative operator D that computes gradients, Hessians, Jacobians, and arbitrary-order derivative tensors at machine precision. $D(D(f))$ gives Hessians, $D(D(D(f)))$ gives third-order tensors for skewness of maximum likelihood estimators, and so on to any order. Works through any R code including loops, branches, and control flow.

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Contents

nabla-package	2
beta	4
D	4
deriv	5
deriv_n	6
differentiate_n	7
dual	7
dual-arithmetic	8
dual-atan2	10
dual-coerce	11
dual-combine	11
dual-is-numeric	12
dual-log	13
dual-math	13
dual-math2	14
dual-maxmin	15
dual-show	16
dual-summary	16
dual_constant	17
dual_constant_n	18
dual_variable	18
dual_variable_n	19
dual_vector	19
dual_vector-access	20
dual_vector-class	21
dualr-class	21
erf	21
erfc	22
gradient	23
hessian	23
is_dual	24
jacobian	24
lbeta	25
psigamma	26
value	27
Index	28

nabla-package

nabla: Exact Derivatives via Automatic Differentiation

Description

Implements forward-mode automatic differentiation using dual numbers with S4 classes. Supports exact arbitrary-order derivatives through recursive nesting of duals, with high-level functions for computing gradients, Hessian matrices, and Jacobians of arbitrary functions.

Core Types

- `dual` Constructor for dual numbers.
- `dual_variable` Shorthand for `dual(x, 1)`.
- `dual_constant` Shorthand for `dual(x, 0)`.
- `dual_vector` Container for indexable dual vectors.

Accessors

- `value` Extract the primal value.
- `deriv` Extract the derivative component.

Higher-Order Derivatives

- `dual_variable_n` Create a dual seeded for n-th order differentiation.
- `deriv_n` Extract the k-th derivative from a nested dual result.
- `differentiate_n` Compute $f(x)$ and all derivatives up to order n.

Multi-Parameter Derivatives

- `D` Composable total derivative operator. $D(f)$ returns the derivative function; apply k times for k-th order tensors.
- `gradient` Gradient of a scalar-valued function.
- `hessian` Hessian matrix of a scalar-valued function.
- `jacobian` Jacobian matrix of a vector-valued function.

Author(s)

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References

Baydin, A. G., Pearlmutter, B. A., Radul, A. A., & Siskind, J. M. (2018). Automatic differentiation in machine learning: a survey. *Journal of Machine Learning Research*, 18(153), 1–43.

See Also

Related CRAN packages: `dual`, `numDeriv`, `madness`

beta	<i>Beta function for dual numbers</i>
------	---------------------------------------

Description

Computed as $\exp(\text{lbeta}(a, b))$.

Usage

```
beta(a, b)

## S4 method for signature 'numeric,numeric'
beta(a, b)

## S4 method for signature 'ANY,ANY'
beta(a, b)
```

Arguments

a	A numeric or dual value.
b	A numeric or dual value.

Value

beta(a, b) with derivative.

Examples

```
beta(2, 3)
a <- dual_variable(2)
value(beta(a, 3))
```

D	<i>Composable total derivative operator</i>
---	---

Description

$D(f)$ returns the derivative of f as a new function. $D(f, x)$ evaluates the derivative at x . $D(D(f))$ composes for second-order derivatives, and so on.

Usage

```
D(f, x = NULL, order = 1L)
```

Arguments

f	A function taking a parameter vector (via <code>x[i]</code> indexing) and returning a scalar, list, or <code>dual_vector</code> .
x	Optional numeric vector. If provided, evaluates $D(f)(x)$.
order	Derivative order (default 1). $order = k$ applies D k times.

Details

Each application of D appends one n -dimension to the output shape, where $n = \text{length}(x)$:

- For $f: \mathbb{R}^n \rightarrow \mathbb{R}$: D gives (n) gradient, D^2 gives (n, n) Hessian, D^3 gives (n, n, n) , etc.
- For $f: \mathbb{R}^n \rightarrow \mathbb{R}^m$: D gives (m, n) Jacobian, D^2 gives (m, n, n) , etc.

The composability works because the S4 dispatch for `dualr` arithmetic handles nested duals recursively. When $D(f)$ is called with dual inputs (from an outer D), derivative propagation is automatic.

`gradient()`, `hessian()`, and `jacobian()` are convenience wrappers: `gradient(f, x)` is $D(f, x)$, `hessian(f, x)` is $D(f, x, \text{order} = 2)$, and `jacobian(f, x)` is $D(f, x)$.

Value

If `x` is `NULL`, a function. Otherwise, a numeric vector, matrix, or array of the appropriate tensor shape.

Examples

```
f <- function(x) x[1]^2 * x[2]
D(f, c(3, 4))
D(f, c(3, 4), order = 2)

g <- function(x) list(x[1] * x[2], x[1]^2)
D(g, c(2, 3))

Df <- D(f)
DDf <- D(Df)
DDf(c(3, 4))
```

 deriv

Extract the derivative (tangent) part of a dual number

Description

Extract the derivative (tangent) part of a dual number

Usage

```
deriv(d)

## S4 method for signature 'dualr'
deriv(d)

## S4 method for signature 'numeric'
deriv(d)
```

Arguments

d A dual object.

Value

The deriv slot.

Examples

```
deriv(dual(3, 1))
```

deriv_n

Extract the k-th derivative from a nested dual result

Description

After evaluating a function on a dual created by `dual_variable_n`, use `deriv_n` to extract any derivative from 0 (the function value) up to the seeded order.

Usage

```
deriv_n(d, k)
```

Arguments

d A (possibly nested) dual number, or a numeric.
k A non-negative integer: 0 for the function value, 1 for the first derivative, etc.

Value

A numeric value.

Examples

```
x <- dual_variable_n(1, order = 3)
r <- exp(x)
deriv_n(r, 0)
deriv_n(r, 1)
deriv_n(r, 2)
deriv_n(r, 3)
```

differentiate_n	<i>Compute a function value and all derivatives up to order n</i>
-----------------	---

Description

Evaluates f at a dual variable seeded for order n , returning the function value and all derivatives from 1 to n .

Usage

```
differentiate_n(f, x, order)
```

Arguments

<code>f</code>	A function of one numeric argument.
<code>x</code>	A numeric value at which to differentiate.
<code>order</code>	A positive integer: the maximum derivative order.

Value

A named list with components `value`, `d1`, `d2`, ..., `d<order>`.

Examples

```
differentiate_n(sin, pi/4, order = 4)
```

dual	<i>Create a dual number</i>
------	-----------------------------

Description

Create a dual number

Usage

```
dual(value, deriv = 0)
```

Arguments

value The primal value (numeric or dual for nesting).
 deriv The derivative component (numeric or dual for nesting). Defaults to 0.

Value

A dual object.

Examples

```
x <- dual(3, 1)
value(x)
deriv(x)
```

dual-arithmetic *Arithmetic and comparison operators for dual numbers*

Description

Implements arithmetic (+, -, *, /, ^), comparison (==, !=, <, >, <=, >=), and logical (&, |) operators. Derivatives follow standard calculus rules (sum, product, quotient, power, chain).

Usage

```
## S4 method for signature 'dualr,dualr'
e1 + e2

## S4 method for signature 'dualr,numeric'
e1 + e2

## S4 method for signature 'numeric,dualr'
e1 + e2

## S4 method for signature 'dualr,dualr'
e1 - e2

## S4 method for signature 'dualr,numeric'
e1 - e2

## S4 method for signature 'numeric,dualr'
e1 - e2

## S4 method for signature 'dualr,dualr'
e1 * e2

## S4 method for signature 'dualr,numeric'
e1 * e2
```

```
## S4 method for signature 'numeric,dualr'  
e1 * e2  
  
## S4 method for signature 'dualr,dualr'  
e1 / e2  
  
## S4 method for signature 'dualr,numeric'  
e1 / e2  
  
## S4 method for signature 'numeric,dualr'  
e1 / e2  
  
## S4 method for signature 'dualr,dualr'  
e1 ^ e2  
  
## S4 method for signature 'dualr,numeric'  
e1 ^ e2  
  
## S4 method for signature 'numeric,dualr'  
e1 ^ e2  
  
## S4 method for signature 'dualr,dualr'  
Ops(e1, e2)  
  
## S4 method for signature 'dualr,numeric'  
Ops(e1, e2)  
  
## S4 method for signature 'numeric,dualr'  
Ops(e1, e2)  
  
## S4 method for signature 'dualr,missing'  
e1 + e2  
  
## S4 method for signature 'dualr,missing'  
e1 - e2  
  
## S4 method for signature 'dualr'  
!x
```

Arguments

e1, e2	Dual or numeric operands.
x	A dual number (for unary !).

Value

A dual for arithmetic ops; logical for comparisons.

Examples

```
x <- dual_variable(3)
y <- dual_variable(4)

value(x + y)
deriv(x * x)
value(x^2)
deriv(x^2)

x < y
x == y
```

dual-atan2

Two-argument arctangent for dual numbers

Description

Two-argument arctangent for dual numbers

Usage

```
## S4 method for signature 'dualr,dualr'
atan2(y, x)

## S4 method for signature 'dualr,numeric'
atan2(y, x)

## S4 method for signature 'numeric,dualr'
atan2(y, x)
```

Arguments

y A dual or numeric.
x A dual or numeric.

Value

A dual representing atan2(y, x) with correct derivative.

Examples

```
y <- dual_variable(1)
x <- dual_constant(1)
result <- atan2(y, x)
value(result)
```

dual-coerce	<i>Coerce dual to numeric</i>
-------------	-------------------------------

Description

Extracts the primal value, discarding the derivative.

Usage

```
## S4 method for signature 'dualr'  
as.numeric(x, ...)
```

Arguments

x	A dual object.
...	Ignored.

Value

Numeric value.

Examples

```
x <- dual(3.14, 1)  
as.numeric(x)
```

dual-combine	<i>Combine dual numbers into a dual_vector</i>
--------------	--

Description

Combine dual numbers into a dual_vector

Usage

```
## S4 method for signature 'dualr'  
c(x, ..., recursive = FALSE)
```

Arguments

x	A dual number.
...	Additional duals or numerics.
recursive	Ignored.

Value

A `dual_vector`.

Examples

```
x <- dual_variable(1)
y <- dual_variable(2)
dv <- c(x, y)
length(dv)
```

dual-is-numeric

Check if a dual number is numeric

Description

Returns TRUE for dual numbers so that defensive type checks pass.

Usage

```
## S4 method for signature 'dualr'
is.numeric(x)
```

Arguments

x A dual object.

Value

TRUE.

Examples

```
is.numeric(dual(1, 0))
```

dual-log

Logarithm with optional base for dual numbers

Description

Logarithm with optional base for dual numbers

Usage

```
## S4 method for signature 'dualr'  
log(x, base = exp(1))
```

Arguments

x	A dual number.
base	Numeric base (default: exp(1) for natural log).

Value

A dual representing $\log(x, \text{base})$.

Examples

```
x <- dual_variable(8)  
value(log(x, base = 2))  
deriv(log(x, base = 2))
```

dual-math

Math group generic for dual numbers

Description

Implements all standard mathematical functions for dual numbers via the chain rule: $f(\text{dual}(a, b)) = \text{dual}(f(a), df(a) * b)$.

Supported functions: abs, sign, sqrt, floor, ceiling, trunc, round, exp, expm1, log, log2, log10, log1p, cos, sin, tan, cospi, sinpi, tanpi, acos, asin, atan, cosh, sinh, tanh, acosh, asinh, atanh, gamma, lgamma, digamma, trigamma, cumsum, factorial, lfactorial.

Usage

```
## S4 method for signature 'dualr'
exp(x)

## S4 method for signature 'dualr'
sqrt(x)

## S4 method for signature 'dualr'
Math(x)
```

Arguments

x A dual number.

Value

A dual with the function applied to the value and the derivative propagated via the chain rule.

Examples

```
x <- dual_variable(pi / 4)
value(sin(x))
deriv(sin(x))

y <- dual_variable(2)
value(exp(y))
deriv(exp(y))
deriv(log(y))
```

dual-math2

Math2 group generic for dual numbers

Description

Implements round and signif for dual numbers. These are piecewise constant functions, so the derivative is zero almost everywhere.

Usage

```
## S4 method for signature 'dualr'
Math2(x, digits)
```

Arguments

x A dual number.
digits Integer; number of digits for rounding.

Value

A dual with the rounded value and zero derivative.

Examples

```
x <- dual_variable(3.14159)
value(round(x, 2))
deriv(round(x, 2))
```

dual-maxmin

Piecewise max and min for dual numbers

Description

Compares on value and propagates the derivative of the selected branch.

Usage

```
## S4 method for signature 'dualr'
max(x, ..., na.rm = FALSE)

## S4 method for signature 'dualr'
min(x, ..., na.rm = FALSE)
```

Arguments

x	A dual number.
...	Additional dual or numeric values.
na.rm	Ignored.

Value

A dual representing the max or min.

Examples

```
x <- dual_variable(3)
y <- dual_variable(5)
value(max(x, y))
value(min(x, y))
```

dual-show	<i>Display a dual number</i>
-----------	------------------------------

Description

Display a dual number

Usage

```
## S4 method for signature 'dualr'
show(object)

## S4 method for signature 'dual_vector'
show(object)
```

Arguments

object A dual object.

Value

Invisible NULL; called for side effect of printing.

Examples

```
x <- dual(3, 1)
x

dv <- dual_vector(dual(1, 0), dual(2, 1))
dv
```

dual-summary	<i>Summary group generic for dual numbers</i>
--------------	---

Description

Implements sum, prod, min, max, range, any, and all for dual numbers. Derivatives are propagated correctly through sum (additive) and prod (multiplicative).

Usage

```
## S4 method for signature 'dualr'
Summary(x, ..., na.rm = FALSE)
```

Arguments

x	A dual number.
...	Additional dual or numeric values.
na.rm	Logical; ignored (present for generic compatibility).

Value

A dual for sum/prod/min/max; a dual_vector for range; logical for any/all.

Examples

```
x <- dual_variable(2)
y <- dual_variable(5)
value(sum(x, y))
value(prod(x, y))
```

dual_constant	<i>Create a dual constant (derivative seed = 0)</i>
---------------	---

Description

Wraps a numeric value as a dual with zero derivative, representing a constant with respect to the differentiation variable.

Usage

```
dual_constant(x)
```

Arguments

x	A numeric value.
---	------------------

Value

A dual with value = x and deriv = 0.

Examples

```
k <- dual_constant(5)
deriv(k)
```

dual_constant_n *Create a constant dual for n-th order differentiation*

Description

Wraps a numeric value as a nested dual with all derivative components zero, representing a constant with respect to the differentiation variable at nesting depth n.

Usage

```
dual_constant_n(x, order)
```

Arguments

x A numeric value.
 order A non-negative integer specifying the nesting depth.

Value

A (possibly nested) dual number with zero derivatives.

Examples

```
k <- dual_constant_n(5, order = 3)
deriv_n(k, 1)
deriv_n(k, 2)
deriv_n(k, 3)
```

dual_variable *Create a dual variable (derivative seed = 1)*

Description

Convenience constructor for the independent variable when computing derivatives. Sets `deriv = 1` so that the output's derivative slot contains df/dx .

Usage

```
dual_variable(x)
```

Arguments

x A numeric value.

Value

A dual with `value = x` and `deriv = 1`.

Examples

```
x <- dual_variable(2)
deriv(x^2)
```

dual_variable_n	<i>Create a dual seeded for n-th order differentiation</i>
-----------------	--

Description

Recursively nests dual numbers to enable exact computation of derivatives up to order n . The variable is seeded so that after evaluating a function f , the k -th derivative can be extracted with `deriv_n(result, k)`.

Usage

```
dual_variable_n(x, order)
```

Arguments

<code>x</code>	A numeric value at which to differentiate.
<code>order</code>	A positive integer specifying the derivative order.

Value

A (possibly nested) dual number.

Examples

```
x <- dual_variable_n(2, order = 3)
r <- x^4
deriv_n(r, 3)
```

dual_vector	<i>Create a vector of dual numbers</i>
-------------	--

Description

Wraps a list of dual objects in a container that supports `[]` indexing and `length()`, so that user functions can use natural `theta[1]` notation.

Usage

```
dual_vector(...)
```

Arguments

... Dual objects, or a single list of dual objects.

Value

A dual_vector.

Examples

```
dv <- dual_vector(dual(1, 0), dual(2, 1))
length(dv)
value(dv[1])
```

dual_vector-access *Indexing and length for dual_vector*

Description

Indexing and length for dual_vector

Usage

```
## S4 method for signature 'dual_vector,numeric'
x[i, j, ..., drop = TRUE]

## S4 method for signature 'dual_vector'
length(x)
```

Arguments

x A dual_vector.
i Numeric index.
j, drop, ... Ignored (present for generic compatibility).

Value

A single dual for scalar index; a dual_vector for vector index; an integer for length.

Examples

```
dv <- dual_vector(dual(10, 1), dual(20, 0), dual(30, 0))
value(dv[1])
length(dv)
```

dual_vector-class *Dual Number Vector*

Description

A container for multiple dual numbers that supports indexing with `[]` and `[[`, allowing log-likelihood functions to be written with `theta[1]`, `theta[2]` notation.

Slots

`.Data` List of dual objects.

dualr-class *Dual Number Class for Automatic Differentiation*

Description

S4 class representing a dual number $a + b\varepsilon$ where $\varepsilon^2 = 0$. The `value` slot holds the primal value and the `deriv` slot holds the tangent (derivative) component. Both slots accept ANY type to support nested duals for higher-order derivatives.

Slots

`value` The primal (function) value. Numeric for first-order duals, or another dual for higher-order.
`deriv` The tangent (derivative) component. Numeric for first-order duals, or another dual for higher-order.

erf *Error function*

Description

Computes $\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$.

Usage

```
erf(x)

## S4 method for signature 'numeric'
erf(x)

## S4 method for signature 'dualr'
erf(x)
```

Arguments

x A numeric or dual value.

Value

The error function value. For dual input, returns a dual with derivative $(2/\sqrt{\pi})e^{-x^2}$.

Examples

```
erf(1)
x <- dual_variable(1)
value(erf(x))
```

erfc

Complementary error function

Description

Computes $\text{erfc}(x) = 1 - \text{erf}(x)$.

Usage

```
erfc(x)

## S4 method for signature 'numeric'
erfc(x)

## S4 method for signature 'dualr'
erfc(x)
```

Arguments

x A numeric or dual value.

Value

The complementary error function value.

Examples

```
erfc(1)
x <- dual_variable(0)
value(erfc(x))
```


Value

A $p \times p$ numeric matrix (the Hessian).

Examples

```
f <- function(x) -(x[1] - 3)^2 - (x[2] - 5)^2
hessian(f, c(1, 2))
```

is_dual	<i>Test whether an object is a dual number</i>
---------	--

Description

Test whether an object is a dual number

Usage

```
is_dual(x)
```

Arguments

`x` An object.

Value

Logical.

Examples

```
is_dual(dual(1, 0))
is_dual(42)
```

jacobian	<i>Compute the Jacobian of a vector-valued function</i>
----------	---

Description

Computes the first derivative of f at x using forward-mode AD. Equivalent to $D(f, x)$. For $f: \mathbb{R}^p \rightarrow \mathbb{R}^m$, returns an $m \times p$ matrix. For scalar-valued f , returns a length- p gradient vector.

Usage

```
jacobian(f, x)
```

Arguments

- f A function taking a parameter vector and returning a scalar, list of scalars, or a dual_vector.
- x A numeric vector of parameter values (length p).

Value

An $m \times p$ numeric matrix for vector-valued f, or a numeric vector of length p for scalar-valued f.

Examples

```
f <- function(x) {
  a <- x[1]; b <- x[2]
  list(a * b, a^2, sin(b))
}
jacobian(f, c(2, pi/4))

g <- function(x) x[1]^2 + x[2]^2
jacobian(g, c(3, 4))
```

lbeta

Log-beta function for dual numbers

Description

Log-beta function for dual numbers

Usage

```
lbeta(a, b)

## S4 method for signature 'numeric,numeric'
lbeta(a, b)

## S4 method for signature 'dualr,dualr'
lbeta(a, b)

## S4 method for signature 'dualr,numeric'
lbeta(a, b)

## S4 method for signature 'numeric,dualr'
lbeta(a, b)
```

Arguments

- a A numeric or dual value.
- b A numeric or dual value.

Value

lbeta(a, b) with derivative via digamma.

Examples

```
lbeta(2, 3)
a <- dual_variable(2)
value(lbeta(a, 3))
```

psigamma

Polygamma function for dual numbers

Description

Computes $\psi^{(n)}(x)$ where n is the derivative order. The derivative of $\psi^{(n)}(x)$ is $\psi^{(n+1)}(x)$.

Usage

```
psigamma(x, deriv = 0L)

## S4 method for signature 'numeric'
psigamma(x, deriv = 0L)

## S4 method for signature 'dualr'
psigamma(x, deriv = 0L)
```

Arguments

`x` A numeric or dual value.
`deriv` Integer derivative order (0 = digamma, 1 = trigamma, etc.).

Value

The polygamma function value.

Examples

```
psigamma(1, deriv = 0)
x <- dual_variable(2)
value(psigamma(x, deriv = 1))
```

value	<i>Extract the value (primal) part of a dual number</i>
-------	---

Description

Extract the value (primal) part of a dual number

Usage

```
value(d)
```

```
## S4 method for signature 'dualr'  
value(d)
```

```
## S4 method for signature 'numeric'  
value(d)
```

Arguments

d A dual object.

Value

The value slot.

Examples

```
value(dual(3, 1))
```

Index

!, dualr-method (dual-arithmetic), 8
*, dualr, dualr-method (dual-arithmetic), 8
*, dualr, numeric-method (dual-arithmetic), 8
*, numeric, dualr-method (dual-arithmetic), 8
+, dualr, dualr-method (dual-arithmetic), 8
+, dualr, missing-method (dual-arithmetic), 8
+, dualr, numeric-method (dual-arithmetic), 8
+, numeric, dualr-method (dual-arithmetic), 8
-, dualr, dualr-method (dual-arithmetic), 8
-, dualr, missing-method (dual-arithmetic), 8
-, dualr, numeric-method (dual-arithmetic), 8
-, numeric, dualr-method (dual-arithmetic), 8
/, dualr, dualr-method (dual-arithmetic), 8
/, dualr, numeric-method (dual-arithmetic), 8
/, numeric, dualr-method (dual-arithmetic), 8
[, dual_vector, numeric-method (dual_vector-access), 20
^, dualr, dualr-method (dual-arithmetic), 8
^, dualr, numeric-method (dual-arithmetic), 8
^, numeric, dualr-method (dual-arithmetic), 8
as.numeric, dualr-method (dual-coerce), 11
atan2, dualr, dualr-method (dual-atan2), 10
atan2, dualr, numeric-method (dual-atan2), 10
atan2, numeric, dualr-method (dual-atan2), 10
beta, 4
beta, ANY, ANY-method (beta), 4
beta, numeric, numeric-method (beta), 4
c, dualr-method (dual-combine), 11
D, 3, 4
deriv, 3, 5
deriv, dualr-method (deriv), 5
deriv, numeric-method (deriv), 5
deriv_n, 3, 6
differentiate_n, 3, 7
dual, 3, 7
dual-arithmetic, 8
dual-atan2, 10
dual-coerce, 11
dual-combine, 11
dual-is-numeric, 12
dual-log, 13
dual-math, 13
dual-math2, 14
dual-maxmin, 15
dual-show, 16
dual-summary, 16
dual_constant, 3, 17
dual_constant_n, 18
dual_variable, 3, 18
dual_variable_n, 3, 6, 19
dual_vector, 3, 19
dual_vector-access, 20
dual_vector-class, 21
dualr-class, 21
erf, 21

erf, dualr-method (erf), 21
erf, numeric-method (erf), 21
erfc, 22
erfc, dualr-method (erfc), 22
erfc, numeric-method (erfc), 22
exp, dualr-method (dual-math), 13

gradient, 3, 23

hessian, 3, 23

is.numeric, dualr-method
 (dual-is-numeric), 12
is_dual, 24

jacobian, 3, 24

lbeta, 25
lbeta, dualr, dualr-method (lbeta), 25
lbeta, dualr, numeric-method (lbeta), 25
lbeta, numeric, dualr-method (lbeta), 25
lbeta, numeric, numeric-method (lbeta), 25
length, dual_vector-method
 (dual_vector-access), 20
log, dualr-method (dual-log), 13

Math, dualr-method (dual-math), 13
Math2, dualr-method (dual-math2), 14
max, dualr-method (dual-maxmin), 15
min, dualr-method (dual-maxmin), 15

nabla (nabla-package), 2
nabla-package, 2

Ops, dualr, dualr-method
 (dual-arithmetic), 8
Ops, dualr, numeric-method
 (dual-arithmetic), 8
Ops, numeric, dualr-method
 (dual-arithmetic), 8

psigamma, 26
psigamma, dualr-method (psigamma), 26
psigamma, numeric-method (psigamma), 26

show, dual_vector-method (dual-show), 16
show, dualr-method (dual-show), 16
sqrt, dualr-method (dual-math), 13
Summary, dualr-method (dual-summary), 16

value, 3, 27
value, dualr-method (value), 27
value, numeric-method (value), 27